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THE BIAS IN THE PRESENTATION OF STIMULI WHEN THE UP AND DOWN METHOD IS USED WITH FORCED CHOICE RESPONDING

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SUMMARY PAGE

THE PROBLEM

The up and down method is used in many psychophysical experiments to determine the threshold stimulus. This method attempts to obtain an accurate estimate of the threshold by concentrating stimulus presentations around the threshold. However, if the up and down method is used in conjunction with forced choice responding, the distribution of stimuli presented to a subject will be biased. This results in the disproportionate presentation of stimuli below the threshold and, as a consequence, a bias in the estimate of the threshold calculated from these presentations. This paper sets out to answer the following questions. What is the nature of this bias in stimulus presentation when the up and down method is used with four alternative forced choice responding? Can this bias be corrected by modifying the up and down method?

FINDINGS

The exact nature of the bias induced by forced choice responding in the up and down method can be clearly demonstrated. An example is given for a visual acuity threshold problem. The up and down method can be analyzed theoretically as a Markov chain, and the probability of a particular stimulus being presented can be computed for every trial. The up and down method can be modified to force convergence of stimulus presentations around the threshold value, even in the forced choice case.

ACKNOWLEDGMENTS

I should like to acknowledge Captain James E. Goodson, MSC, USN, and Doctor Ailene Morris for their many stimulating discussions of the ideas contained in this paper.

INTRODUCTION

Dixon and Mood (4) proposed the up and down method as a technique to concentrate testing near the mean of a normal distribution. This technique was soon seen to be an economical way of measuring the psychophysical threshold. Cornsweet (3) and Kappauf (5) illustrated the use of the up and down method, and also referred to other work where this technique has been used to measure sensory thresholds. In the psychological literature the up and down method is sometimes called the staircase method.

If the up and down method is used in conjunction with forced choice responding, then the presentation of the stimuli will tend, after some number of trials, to concentrate not around the threshold stimulus, but rather at levels below the threshold. This is true because the probability of a correct response never goes below 1/m, where m is the number of response alternatives. This results in relatively more stimulus presentations below the threshold. Also, most estimators of the threshold based on the accumulated data after some number of trials will also be biased for the same reason. The object of this paper is to give a precise statement about the effect of this bias, and to offer a modification of the standard up and down method which will correct the bias when using a forced choice method of responding.

The approach taken to examine this bias is as follows. We assume that there is a fixed number of stimuli which will be presented to a subject. We compute the probabilities of each of these stimuli appearing on the next trial of the up and down process. We then compute the expected value of this probability distribution and plot it as a function of the trial number. In this way we show the effect of forced choice responding in driving the mean of the probability distribution to values below the threshold.

The computation of the probability distribution is made possible by formulating the up and down method as a Markov chain (6, 8). By specifying the probability transition matrix and the initial probability distribution of the stimuli at the start of the experiment, and by employing a simple recursive formula from Markov chain theory, the calculation of the probability distribution of the stimuli on each succeeding trial follows quite readily.

DETERMINING A VISUAL ACUITY THRESHOLD WITH A FORCED CHOICE UP AND DOWN METHOD

As an example of how bias can enter into the presentation of stimuli using the up and down method with forced choice responding, consider the following problem.

Let us assume that we want to determine a visual acuity threshold and that we are using Landolt C rings of known gap sizes to measure the threshold. Our definition of the threshold is the size of the gap in the Landolt ring where the probability of detecting the gap is .50. We present a Landolt ring with the gap in one of four orientations (up, right, down, and left) and require a response from the subject indicating his choice of which of the four orientations he detected. We are, therefore, employing a four alternative forced choice method of responding.

If the subject makes a correct response, a smaller gap size is presented on the next trial. If the subject makes a wrong response, a larger gap size is presented on the next trial. The step size is the difference in gap size between adjacent stimuli.

From the sequence of responses emitted by the subject over some number of trials and the associated stimulus values presented we would like to estimate the threshold gap size.

Let us say that we have chosen some gap sizes from a psychometric function relating differing gap sizes to probability of detection. Let's say we have chosen nine different gap sizes from this psychometric function such that the probability of detection of the first stimulus is .90, the probability of detection of the second stimulus is .80, and so on. Let's pick a tenth stimulus whose gap size is so small that the visual system cannot possibly resolve it. Its probability of detection, therefore, is zero.

Now, the probability of detecting a particular gap size is different from the probability of a correct response to that gap size because of the forced choice nature of the task. We can easily derive a formula to determine the probability of a correct response to each gap size. Consider the tree diagram in Figure 1. $S(j)$ indicates the j^{th} stimulus, $p(D|S(j))$ indicates the probability of detecting the gap given that particular size stimulus, and D and $\bar{D}$ represent detect and non-detect states, respectively. With probability $p(D|S(j)$ the subject enters a detect state and emits a correct response with probability one. With probability $1-p(D|S(j)))$ the subject enters the non-detect state, but has a one-fourth chance of emitting a correct response. He has a three-fourths chance of emitting the wrong response. To find the probability of a correct response we sum over all branches leading to a correct response. This brings us to

$$p(\text{correct response}|S(j)) = p\ (D|S(j)) + 1/4(1 - p(D|S(j))$$

Similarly,

$$p(\text{wrong response}\ |S(j)) = 3/4(1 - p(D|S(j))$$

Of course, this little exercise is nothing more than the usual correction for chance when a forced choice method of responding is employed.

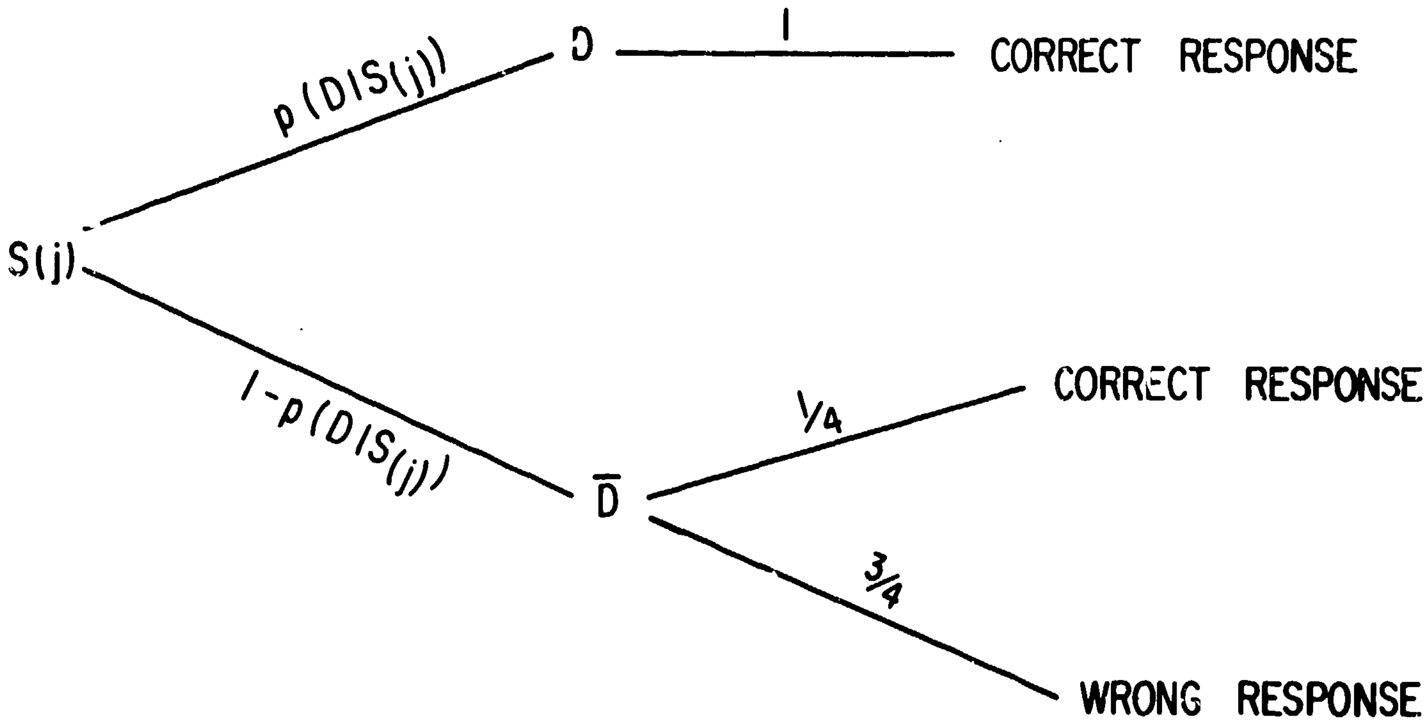

Figure 1. **Tree diagram showing the probabilities of a correct response and wrong response in a four alternative forced choice situation.**

Table I presents the ten stimuli used in our example with their probability of detection, probability of correct response, and probability of wrong response.

FORMULATING THE UP AND DOWN METHOD IN TERMS OF A MARKOV CHAIN

The up and down method can be thought of as a Markov chain. In Markov chain terminology we talk about the probability of transitioning from state i on trial n to state j on trial n+1. We'll denote this probability, p (i, j). The probability of being in a certain state on trial n+1 depends only on what state the chain was in on trial n, and is independent of all previous trials.

The stimulus presented in the up and down method on trial n+1 depends only on the response to the stimulus on trial n, and is independent of the responses on the n-1st trial, n-2nd trial, and so on. The probability, p (i, j), of going from stimulus i, S (i), on trial n to the next <u>smaller</u> stimulus, S (j), on trial n+1 is the probability of a correct response to S (i). The probability, 1-p (i, j), of going from S (i) to the next <u>larger</u> stimulus, S (k), is the probability of a wrong response to S (i).

Table II gives the probability transition matrix for the visual acuity threshold example. We observe from the matrix that we can move to the next smaller gap size by making a correct response, and that we can move to the next larger gap size by making a wrong response. The only exception to this rule is at the beginning and end of the stimulus series. If an incorrect response should be made to the largest gap size, S (1), then S (1) is presented on the next trial. If a correct response happens to be made to the smallest gap size, S (10), then S (10) is presented again on the next trial.

Let $\pi(0)$ be a row vector whose elements are the probabilities of presenting one of the Landolt C stimuli on the initial trial. Markov chain theory provides us with a recursive formula which allows us to calculate the row vector of probabilities on the n^{th} trial. The formula is simply

$$\pi(n + 1) = \pi(n)p$$

where p is the probability transition matrix (1).

SOME RESULTS CONCERNING THE BIAS OF STIMULUS PRESENTATIONS IN THE ILLUSTRATIVE EXAMPLE

Three different row vectors were used to start the up and down process. The first row vector started the process with S (1), the largest stimulus, the second row vector with S (5), the threshold stimulus, and the third row vector started the process with S (10), the undetectable stimulus. Figure 2 shows the expected value of the probability distribution of stimulus values to be presented for these three situations as a function of trial number. We can see from these

Table I

The ten stimuli used in the visual acuity example with their associated probabilities of detection, correct response, and wrong response. S(1) is the largest stimulus and S(10) is the smallest.

Stimulus	Probability of Detection	Probability of Correct Response	Probability of Wrong Response
S(1)	.900	.925	.075
S(2)	.800	.850	.150
S(3)	.700	.775	.225
S(4)	.600	.700	.300
S(5)	.500	.625	.375
S(6)	.400	.550	.450
S(7)	.300	.475	.525
S(8)	.200	.400	.600
S(9)	.100	.325	.675
S(10)	0	.250	.750

Table II

The probability transition matrix for the visual acuity threshold problem. This transition matrix represents the standard up and down method of presenting stimuli.

Stimulus presented on trial n	Stimulus presented on trial n+1									
	S (1)	S (2)	S (3)	S (4)	S (5)	S (6)	S (7)	S (8)	S (9)	S (10)
S (1)	.075	.925	0	0	0	0	0	0	0	0
S (2)	.150	0	.850	0	0	0	0	0	0	0
S (3)	0	.225	0	.775	0	0	0	0	0	0
S (4)	0	0	.300	0	.700	0	0	0	0	0
S (5)	0	0	0	.375	0	.625	0	0	0	0
S (6)	0	0	0	0	.450	0	.550	0	0	0
S (7)	0	0	0	0	0	.525	0	.475	0	0
S (8)	0	0	0	0	0	0	.600	0	.400	0
S (9)	0	0	0	0	0	0	0	.675	0	.325
S (10)	0	0	0	0	0	0	0	0	.750	.250

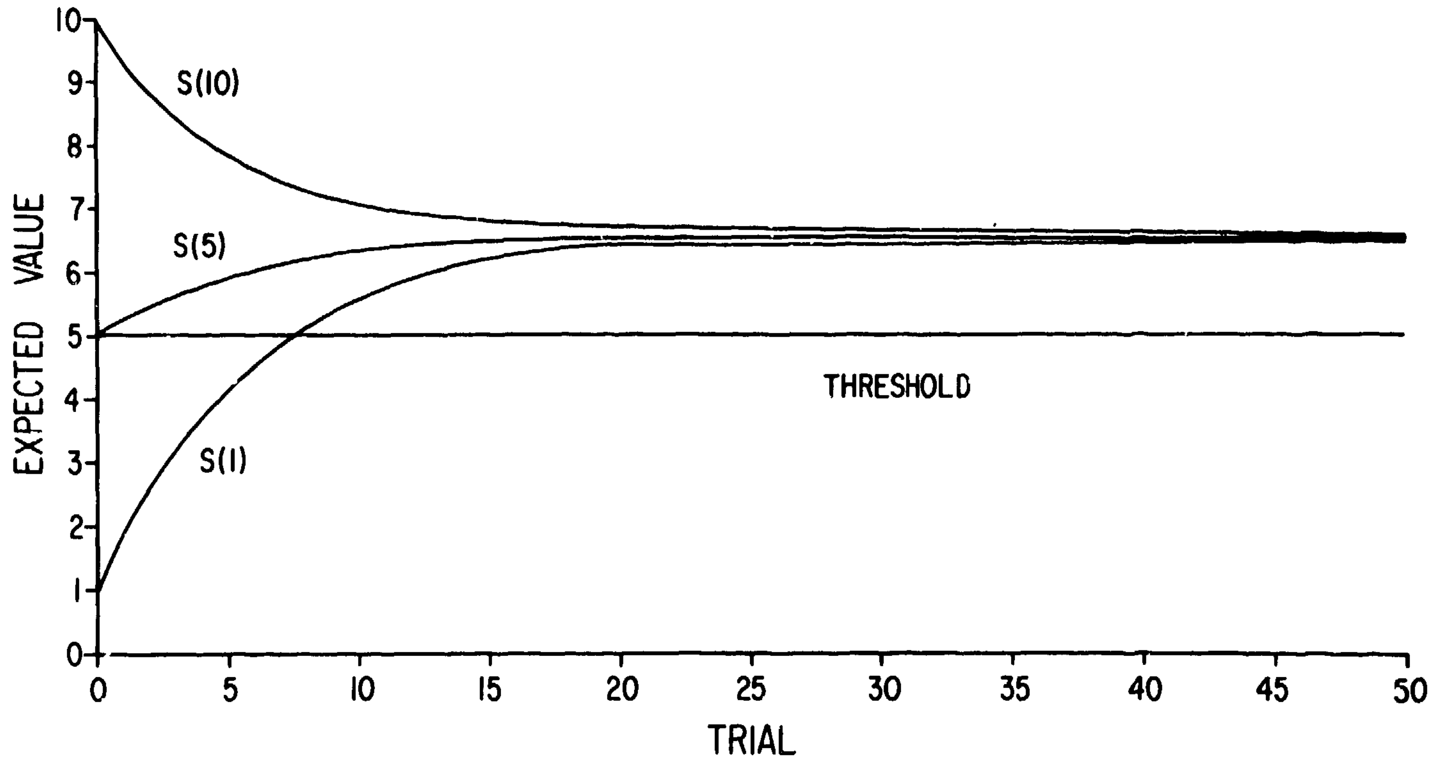

Figure 2. The expected value o: the probability distribution of the stimuli to be presented in the up and down method plotted as a function of trial number. These curves illustrate how the up and down method with four alternative forced choice responding converges to presentation of stimuli below threshold.

curves the bias induced by the forced choice method of responding. After some number of trials, all three curves converge to a value of about 6.6 rather than the threshold value of 5. The mean of the distribution of gap sizes to be presented in the up and down method has been shifted to the smaller gap sizes.

Another way of viewing the bias induced by the forced choice method of responding is to add up the probabilities for S (7), S (8), S (9), and S (10); i.e., those stimuli for which the probability of detection is .30 or less. Table III presents the probability distribution of all ten stimuli, S (1) through S (10), on trials 49 and 50 in the case where the process was started with S (1). By trial 49, the subject will be presented with a stimulus whose probability of detection is only .30 or less, 46 percent of the time. By trial 50, the subject will be presented with a stimulus whose probability of detection is .30 or less, 59 percent of the time. So, instead of concentrating observations around S (5), the threshold stimulus, forced choice responding has driven the up and down process to present stimuli well below the 50 percent threshold on over half the trials.

A PROCEDURE TO CORRECT FOR THE BIAS

How might one ameliorate this effect of forced choice responding on the up and down method? One method which substantially reduces the bias is presented below.

One might think to correct this bias by requiring the subject to emit <u>two</u> correct responses before presenting him with the next smaller stimulus. However, it turns out that this procedure overcompensates for the bias and results in too many presentations <u>above</u> the threshold stimulus.

Since requiring one correct response to present the next smaller stimulus results in a bias below the threshold and requiring two correct responses to present the next smaller stimulus results in a bias above the threshold, it was natural to seek some mixture of these two rules to force the up and down method to concentrate stimulus presentations near threshold. The procedure proposed here to accomplish this is as follows. Generally, on some proportion of trials we require two correct responses before presenting the smaller stimulus on the next trial.

Specifically, let a random number be generated on trial n. If this random number is greater than some fixed value and the subject responds correctly to S (j), present S (j) on trial n+1. No random number is generated on this next trial. If the subject responds correctly to S (j) on trial n+1, present S (j+1) on trial n+2. If the random number generated on trial n is less than the fixed value and the subject responds correctly to S (j), present S (j+1) on trial n+1. If the subject responds incorrectly on any trial, S (j-1) is presented on the next trial.

Table III

The probability distribution of stimuli S (1) through S (10) of trials 49 and 50 with the standard up and down method and four alternative forced choice responding. The process started with the presentation of the largest stimulus, S (1).

Stimulus	Probability of Presentation of S (j) on trial 49	Probability of Presentation of S (j) on trial 50
S (1)	.0006	.0020
S (2)	.0133	.0030
S (3)	.0110	.0501
S (4)	.1293	.0294
S (5)	.0558	.2383
S (6)	.3285	.0825
S (7)	.0908	.3370
S (8)	.2604	.0801
S (9)	.0548	.1459
S (10)	.0556	.0317

This verbal description is aided by Figure 3 which shows the procedure in terms of a partial tree diagram. For sake of concreteness, the stimuli and probabilities are borrowed from the visual acuity example. Let's say S(2) was presented on trial n. The probability of a correct response to S(2) is .85 and the probability of an incorrect response is .15. Let p be the probability that the random number generated on trial n exceeds the fixed value. Therefore, p represents the proportion of trials on which we demand two correct responses to get to the next smaller gap size. S'(2) is the notation for the fact that the subject responded correctly to S(2) on the previous trial, but is presented with S(2) again and must respond correctly on this second presentation of S(2) before moving to S(3). If the subject responds incorrectly to S(2) on trial n or S'(2) on trial n+1, S(1) is presented on the next trial.

We can proceed with a Markov chain formulation just as before. We now have to add the primed states to the probability transition matrix and adjust the probabilities of transitioning to the primed and unprimed states to reflect the value of p.

The probability transition matrix for one value of p (p = .5333) is given in Table IV. This value was selected on the basis of experimentation with different values of p. It gave the best convergence to the desired mean of the probability distribution of stimulus values. So, in effect, in just slightly over half the trials we require the subject to make two correct responses before presenting him with the next smaller gap size.

SOME RESULTS USING THE NEW PROCEDURE

Just as in the previous example, we present in Figure 4 three curves showing the mean of the probability distribution of stimuli to be presented for each of three starting points as a function of trial number. The starting stimulus values were again S(1), S(5), and S(10).

We see that this new up and down method does converge to a better concentration of stimuli around the threshold than does the standard up and down procedure.

Table V gives the probability distribution for S(1) through S(10) on trials 49 and 50 for the modified up and down method. S(1) was used as the starting stimulus in this case. By trial 50 of the modified procedure only about 19 percent of the stimulus presentations have probability of detection of .30 or less. By this trial in the standard up and down method over 50 percent of the presentations were stimuli whose probability of detection was .30 or less.

If we look at the percentage of presentation of stimuli around the threshold, (S(4), S(5), and S(6) whose probabilities of detection are .60, .50, and .40, respectively) then we see that in the standard up and down method

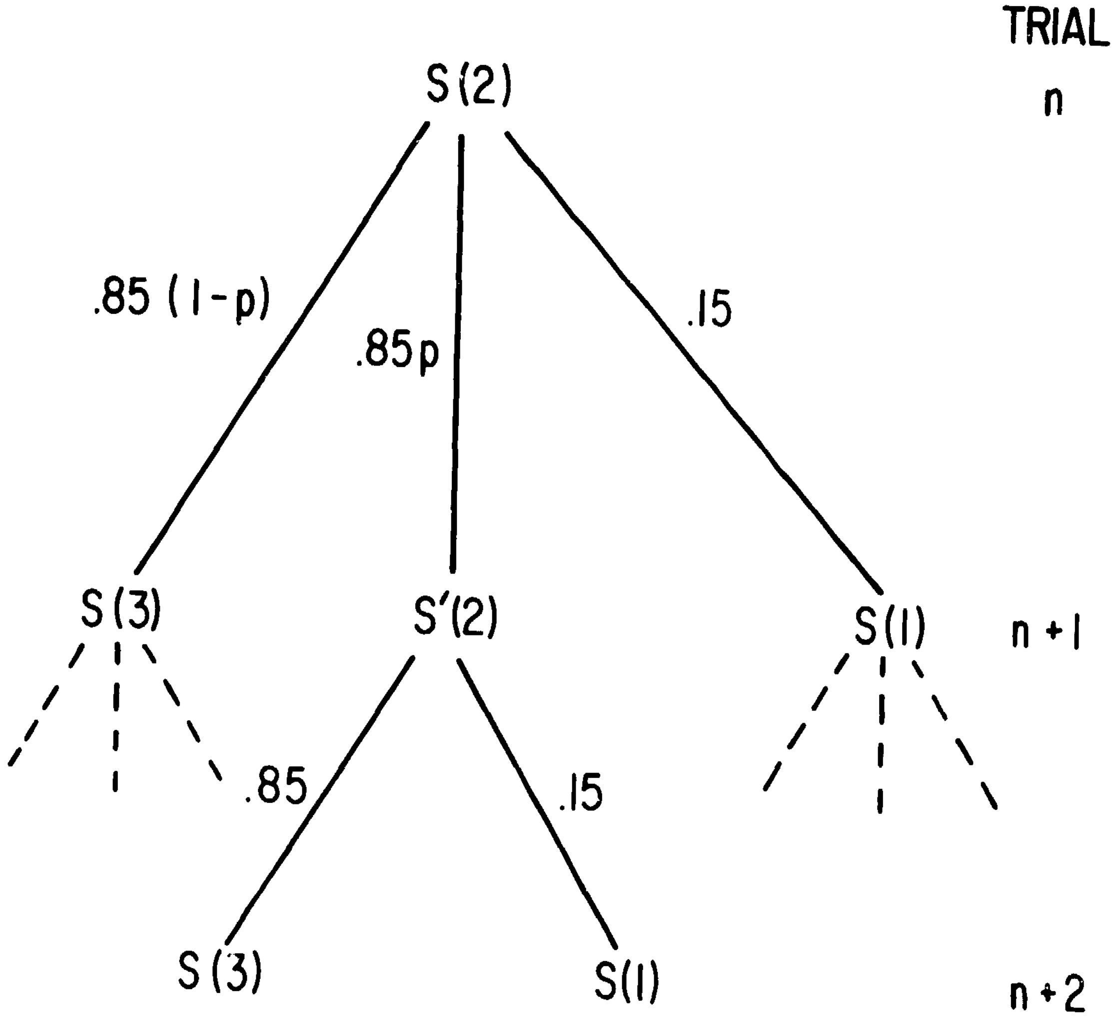

Figure 3. Tree diagram illustrating a modified up and down method. The modification requires two correct responses on a proportion of the trials before the next smaller stimulus is presented.

Table IV

The first half of the probability transition matrix for the visual acuity threshold problem. The modified up and down method of presenting stimuli, as explained in the text, was used to generate this matrix.

Stimulus presented on trial n	Stimulus presented on trial n+1									
	S(1)	S'(1)	S(2)	S'(2)	S(5)	S'(3)	S(4)	S'(4)	S(5)	S'(5)
S(1)	.0750	.4933	.4317	0	0	0	0	0	0	0
S'(1)	.0750	0	.9250	0	0	0	0	0	0	0
S (2)	.1500	0	0	.4533	.3967	0	0	0	0	0
S'(2)	.1500	0	0	0	.8500	0	0	0	0	0
S(3)	0	0	.2250	0	0	.4133	.3617	0	0	0
S'(3)	0	0	.2250	0	0	0	.7750	0	0	0
S(4)	0	0	0	0	.3000	0	0	.3733	.3267	0
S'(4)	0	0	0	0	.3000	0	0	0	.7000	0
S(5)	0	0	0	0	0	0	.3750	0	0	.3333
S'(5)	0	0	0	0	0	0	.3750	0	0	0
S(6)	0	0	0	0	0	0	0	0	.4500	0
S'(6)	0	0	0	0	0	0	0	0	.4500	0
S(7)	0	0	0	0	0	0	0	0	0	0
S'(7)	0	0	0	0	0	0	0	0	0	0
S(8)	0	0	0	0	0	0	0	0	0	0
S'(8)	0	0	0	0	0	0	0	0	0	0
S(9)	0	0	0	0	0	0	0	0	0	0
S'(9)	0	0	0	0	0	0	0	0	0	0
S(10)	0	0	0	0	0	0	0	0	0	0

Table IV
(Continued)

The second half of the probability transition matrix for the modified up and down method

Stimulus presented on trial n	Stimulus presented on trial n+1								
	S(6)	S'(6)	S(7)	S'(7)	S(8)	S'(8)	S(9)	S'(9)	S(10)
S (1)	0	0	0	0	0	0	0	0	0
S'(1)	0	0	0	0	0	0	0	0	0
S (2)	0	0	0	0	0	0	0	0	0
S'(2)	0	0	0	0	0	0	0	0	0
S (3)	0	0	0	0	0	0	0	0	0
S'(3)	0	0	0	0	0	0	0	0	0
S (4)	0	0	0	0	0	0	0	0	0
S'(4)	0	0	0	0	0	0	0	0	0
S (5)	.2917	0	0	0	0	0	0	0	0
S'(5)	.6250	0	0	0	0	0	0	0	0
S (6)	0	.2933	.2567	0	0	0	0	0	0
S'(6)	0	0	.5500	0	0	0	0	0	0
S (7)	.5250	0	0	.2533	.2217	0	0	0	0
S'(7)	.5250	0	0	0	.4750	0	0	0	0
S (8)	0	0	.6000	0	0	.2133	.1867	0	0
S'(8)	0	0	.6000	0	0	0	.4000	0	0
S (9)	0	0	0	0	.6750	0	0	.1733	.1517
S'(9)	0	0	0	0	.6750	0	0	0	.3250
S (10)	0	0	0	0	0	0	.7250	0	.2500

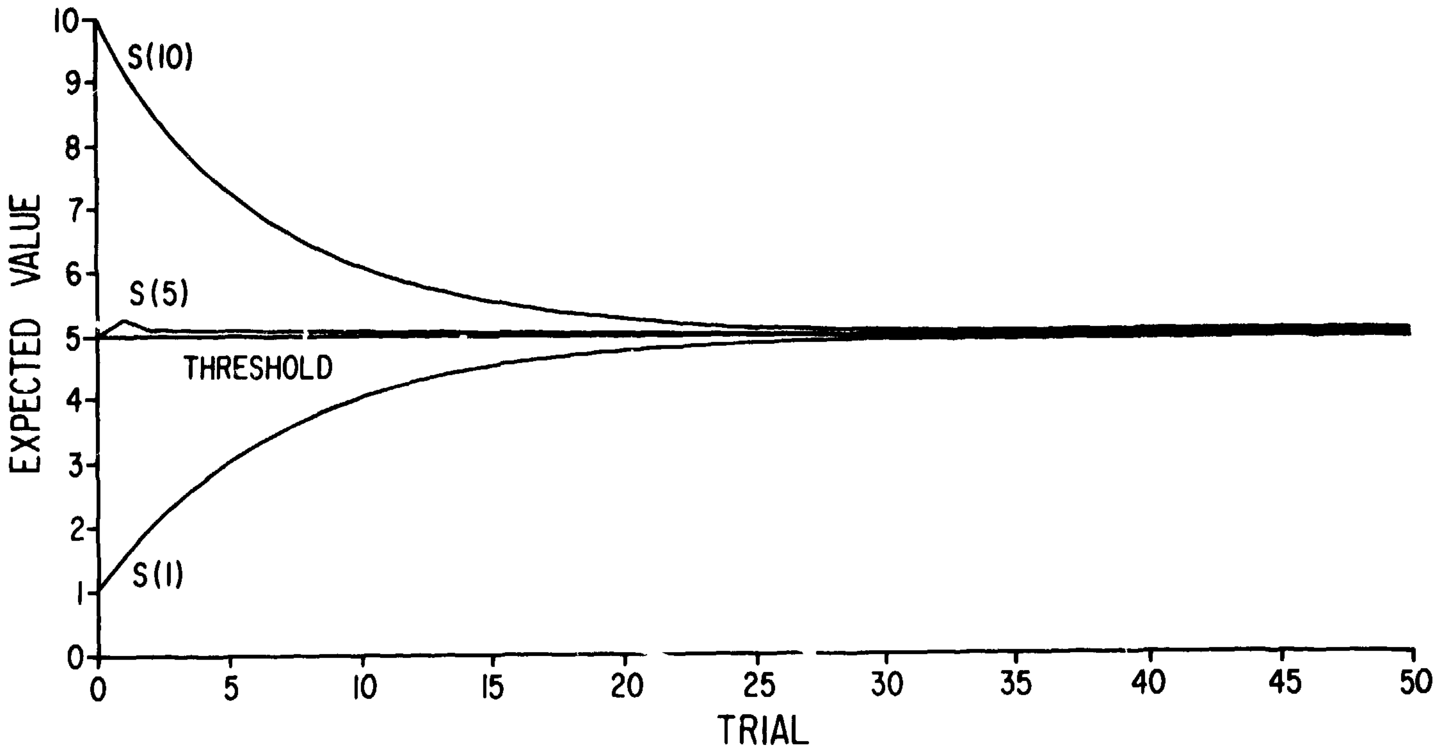

Figure 4. The expected value of the probability distribution of the stimuli to be presented in the modified up and down method plotted as a function of trial number. These curves illustrate how the modified up and down method converges to the threshold even with forced choice responding.

Table V

The probability distribution of stimuli S (1) through S (10) on trials 49 and 50 with the modified up and down method and four alternative forced choice responding. The process started with the presentation of the largest stimulus, S (1).

Stimulus	Probability of presentation of S (j) on trial 49	Probability of presentation of S (j) on trial 50
S (1)	.0132	.0132
S (2)	.0522	.0521
S (3)	.1246	.1246
S (4)	.2002	.2002
S (5)	.2283	.2283
S (6)	.1900	.1900
S (7)	.1168	.1168
S (8)	.0530	.0531
S (9)	.0176	.0176
S (10)	.0042	.0042

these stimuli are presented about 35 percent of the time. In contrast, these stimuli appear about 62 percent of the time in the modified method.

CONCLUDING REMARKS

I have attempted in this paper to bring to light the bias which exists in the standard application of the up and down method when used with forced choice responding. Sooner or later in the process, stimulus presentations will be skewed to the low end of the detection distribution. Exactly when this occurs depends on how far the starting stimulus value is from the true threshold and on the magnitude of the step size (2).

An additional finding is that deriving the exact probability distributions of the stimuli to be presented on the nth trial is made relatively easy by treating the up and down method as a Markov chain. Modification of the standard up and down procedure can also be treated in terms of a Markov chain and its associated probability transition matrix.

One easily implementable strategy has been proposed to negate the effects of this bias. There exist other methods of measuring the psychophysical threshold which are resistant to bias induced by forced choice responding (7).

We have seen, in the example employed, that the modified up and down method does converge to the threshold value. However, if the process has been started some distance away from the threshold value (or the step size used is very small), it will take a considerable number of trials for it to reach the region where it is reasonably close to the threshold.

This finding has some bearing on the choice of an estimator of the threshold value. If we had no prior information about where we were starting the process with regard to the threshold, we might want to adopt a conservative strategy and ignore in our computation of the threshold some number of the initial trials. We could then, for example, average the stimuli presented after this trial number. We would be excluding from our estimation of the threshold those values which are far from the threshold. We would, in addition, reduce the variability of our estimator.

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The up-and-down method is used in many psychophysical experiments to determine the threshold stimulus. This method attempts to obtain an accurate estimate of the threshold by concentrating stimulus presentations around the threshold. However, if the up-and-down method is used in conjunction with forced responding, the distribution of stimuli presented to a subject will be biased. This results in the disproportionate presentation of stimuli below the threshold and, as a consequence

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) a bias in the estimate of the threshold calculated from these presentations. This paper sets out to answer the following questions. What is the nature of this bias in stimulus presentation when the up-and-down method is used with four alternative forced choice responding? Can this bias be corrected by modifying the up-and-down method?

The exact nature of the bias induced by forced choice responding in the up-and-down method can be clearly demonstrated. An example is given for a visual acuity threshold problem. The up-and-down method can be analyzed theoretically as a Markov chain and the probability of a particular stimulus being presented can be computed for every trial. The up-and-down method can be modified to force convergence of stimulus presentations around the threshold value, even in the forced choice case.